Lecture-02 (Part-1)

Fundamentals of metal cutting

A crankshaft before and after machining

Principle of metal cutting

- Difference in hardness of tool and workpiece
- Metal cutting is a chip removal process

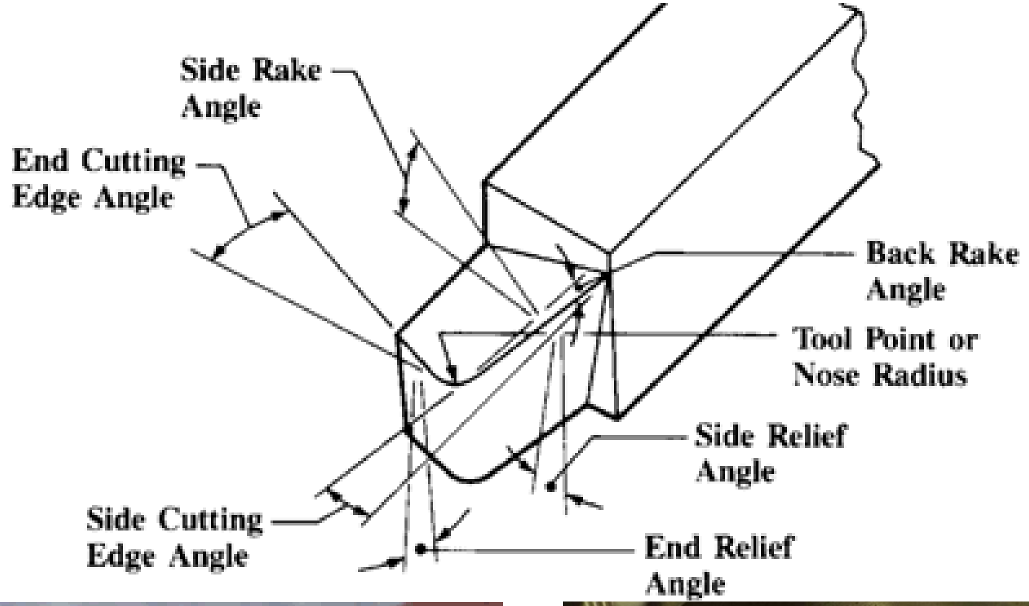
Geometry of single point tool

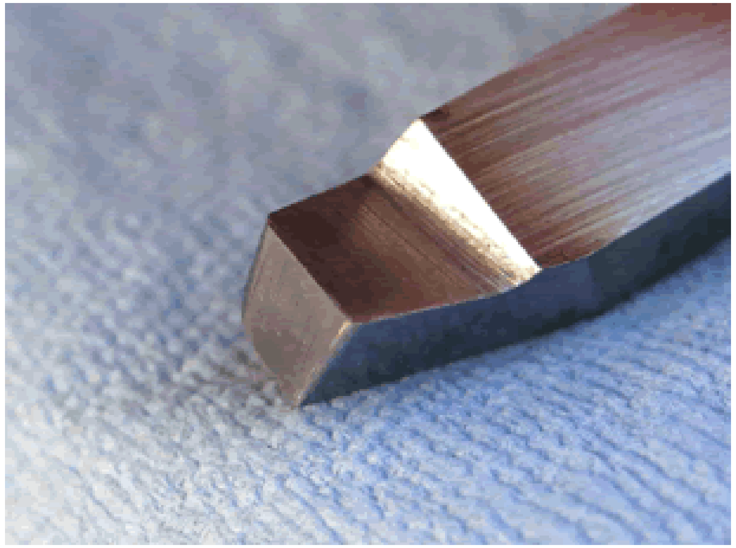
The chip removal process may be performed by cutting tools of definite geometry. These cutting tools can be classified as single point cutting tool, used in lathe, planer and, slotter and multi point cutting tool used in milling, drilling and broaching.

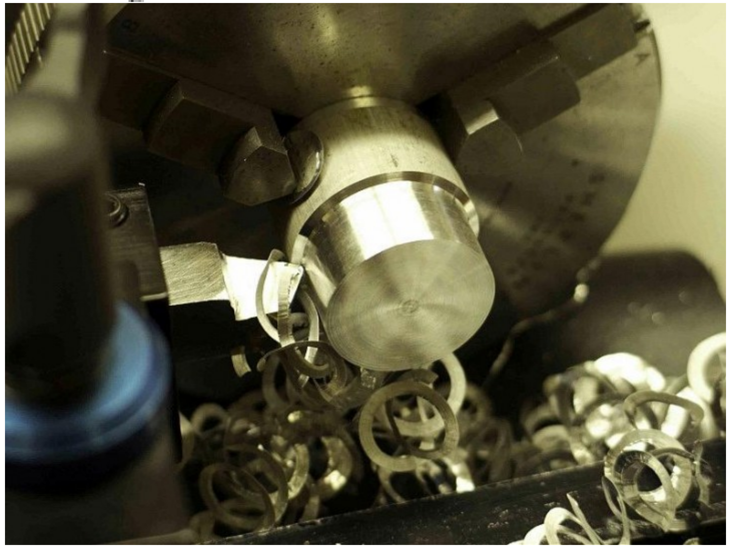
Video link for cutting tool types and geometry:

https://www.youtube.com/watch?v=J63dZsw7Ia4

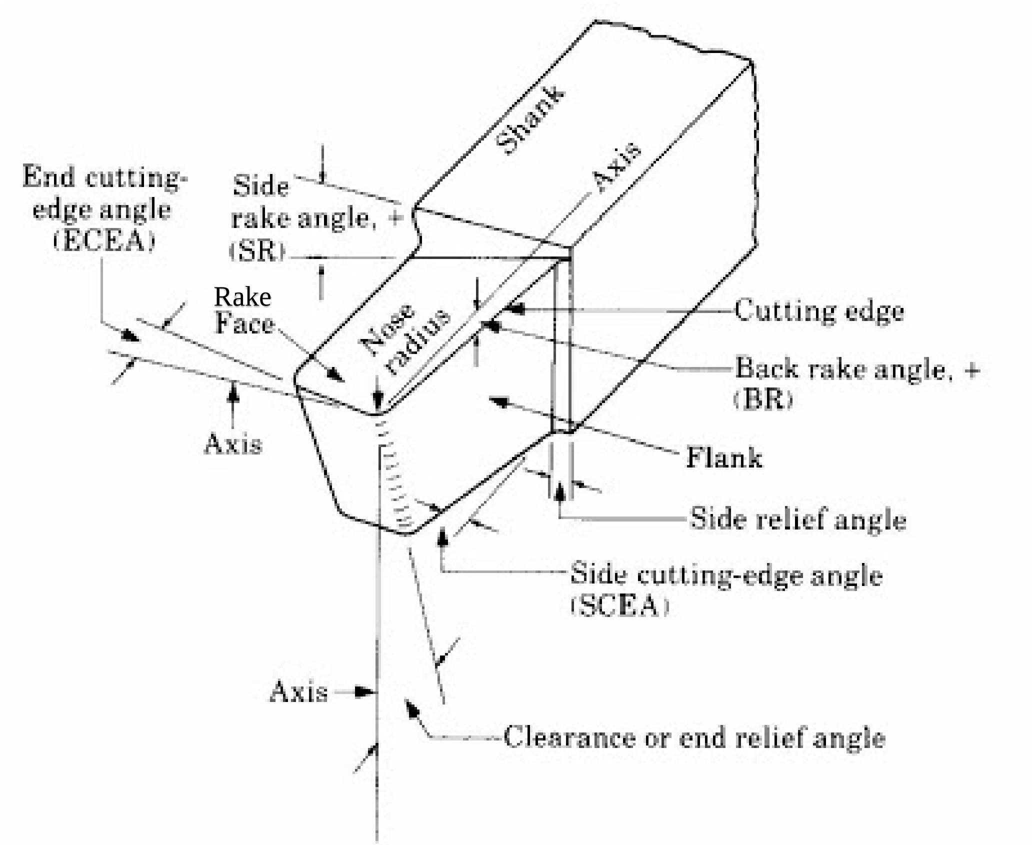
Geometry of single point tool

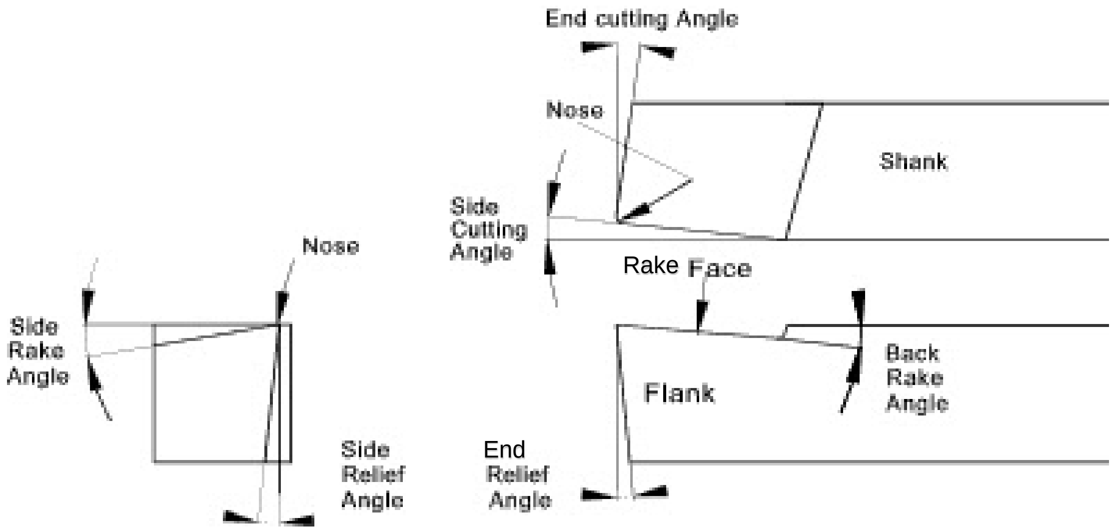






Geometry of single point tool





Video link for understanding tool geometry and metal cutting

https://www.youtube.com/watch?v=Mn9jpqI8rao

https://www.youtube.com/watch?v=bUrp8JMRwx4

Geometry of single point tool

Shank: the shank is used as a tool holder. It is a main body of the tool. It is generally gripped in the tool frame.

Flank: It is a surface of the cutting edge or the surface adjacent to the cutting edge of the tool.

***Face**:* It is the surface of the tool where the chip slides along the top of this surface.

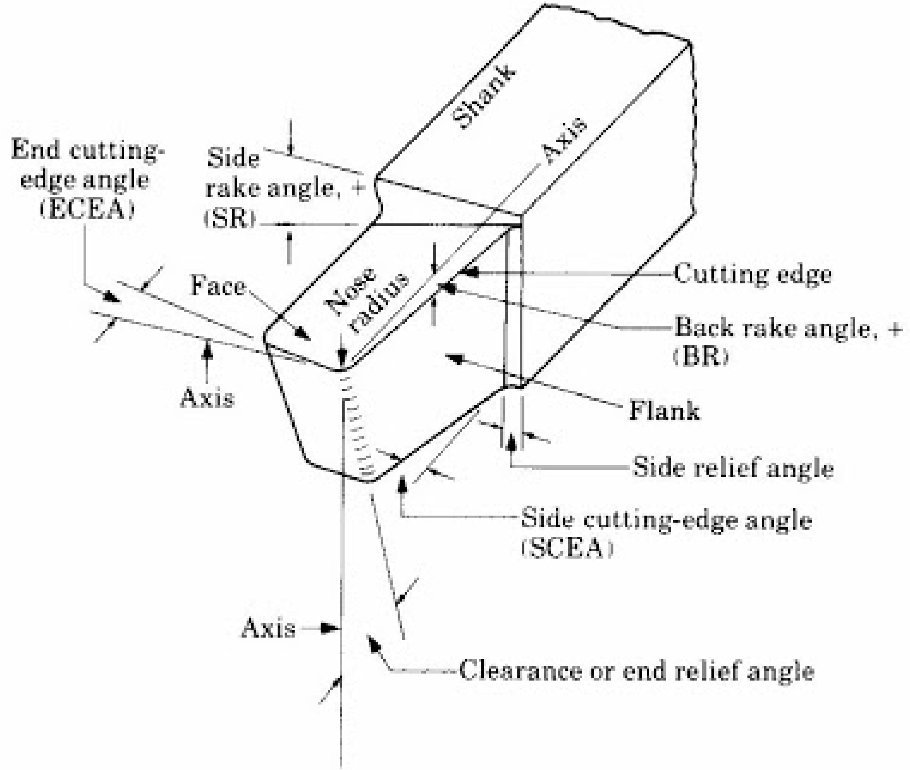
***Base**:* Base is a bearing surface of the tool. This base is held in a tool holder or it is directly clamped in the tool post.

Nose: This is a point where the base cutting edge and the side cutting edge gets intersected.

Cutting edges: It is a face edge on the face of the tool that removes the material from the work piece. There are two cutting edges as side cutting edge and end cutting edge, where the side cutting edge is **major cutting edge** and the end cutting edge is **minor cutting edge**.

Tool angles: Tool angle splay a vital role in the tool cutting action. The tool that comes with proper angles will reduce failures as tool breaking due to high work forces on the work piece. The metal cutting is done more efficiently with generation of little heat.

Noise radius: The nose radius will provide long life and also good surface finish with it sharp point on the nose. It has high stress and leaves in its path of cut. Longer nose radius will give raise to chatter.



Geometry of single point tool

Side cutting edge angle:
It is the angle in between the side cutting edge and the side of the tool shank. This angle is also referred as lead angle.

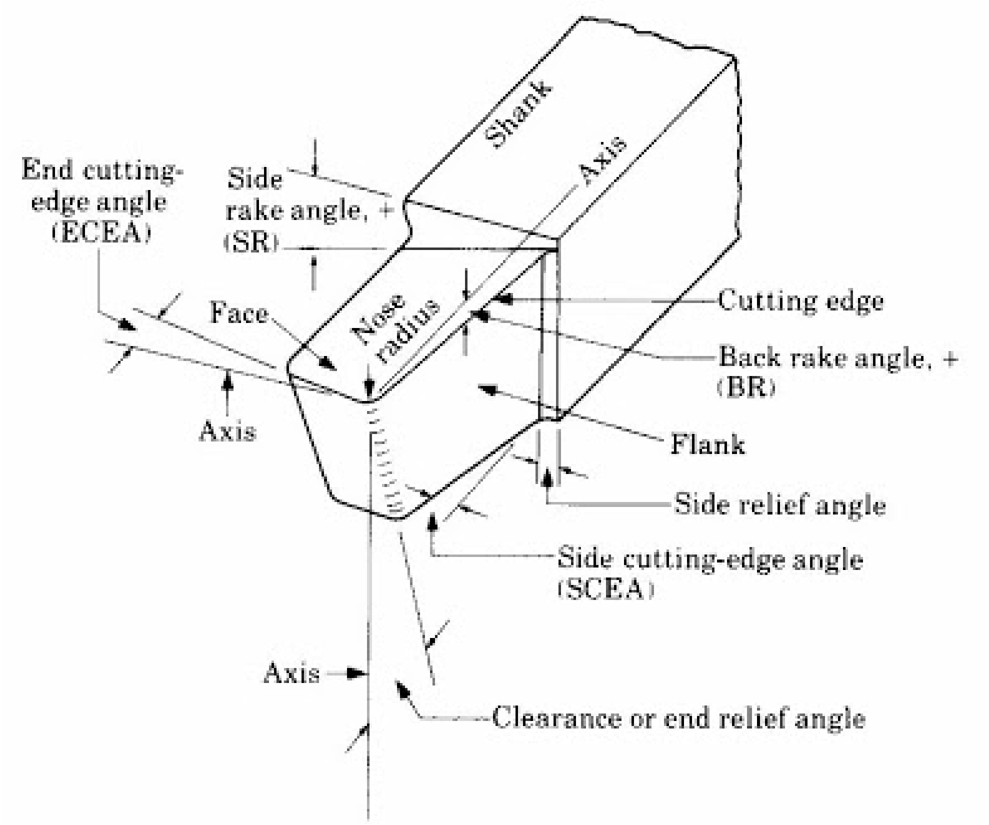
End cutting edge angle:
End cutting edge angle is in between the perpendicular line of the tool shank and the end cutting edge.

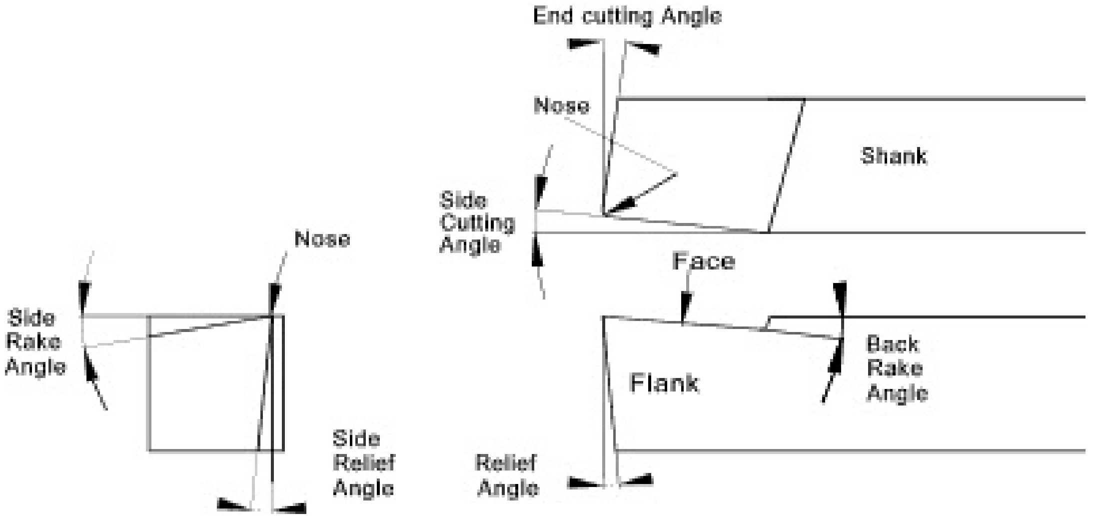
Side relief angle:
The portion of side flank that is immediate below to the side cutting edge and the base perpendicular line of the cutting tool.

End relief angle:
Relief angle is in between the base perpendicular line and end flank.

Back rake angle:
The angle between the face of the tool and the a line parallel to base of the shank in a plane parallel to flank.

Side rake angle:
The angle in between the parallel line of the base and the face of the tool that is measured it the plane perpendicular to the side edge and base.





Right cut tool

A right cut tool is the tool in which the main cutting edge faces the headstock of the lathe, when the tool is clamped and in this case the tool cuts from right to left.

Left cut tool

In this case the main cutting edge faces the tailstock of the lathe and consequently the tool cuts from left to right as shown in figure 2.2.

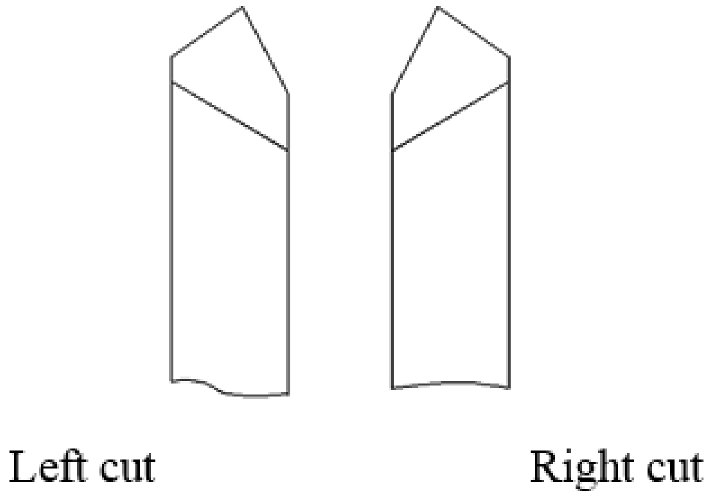


Figure 2.2: Two basic types of single point cutting tools

Requirements of tool materials:

- Cutting tool is subjected to:

1. High temperatures,
2. High contact stresses
3. Rubbing along the tool–chip interface and along the machined surface

- Cutting-tool material must possess:

1. **Hot hardness**
2. **Toughness** and **impact strength**
3. **Thermal shock resistance**
4. **Wear resistance**
5. **Chemical stability** and **inertness**

Requirements of tool materials:

1. High hardness and high hot hardness
2. High wear resistance
3. High strength and toughness (impact resistance)
4. High thermal conductivity
5. Low cost

Characteristics of tool material

- Tool materials may not have all of the desired properties for a particular machining operation

General Characteristics of Tool Materials

Property	High-speed steels	Cast-cobalt alloys	Carbides WC	Carbides TiC	Ceramics	Cubic boron nitride	Single-crystal diamond*
Hardness	83–86 HRA	82–84 HRA 46–62 HRC	90–95 HRA 1800–2400 HK	91–93 HRA 1800–3200 HK	91–95 HRA 2000–3000 HK	4000–5000 HK	7000–8000 HK
Compressive strength, MPa	4100–4500	1500–2300	4100–5850	3100–3850	2750–4500	6900	6900
Transverse rupture strength, MPa	2400–4800	1380–2050	1050–2600	1380–1900	345–950	700	1350
Impact strength, J	1.35–8	0.34–1.25	0.34–1.35	0.79–1.24	<0.1	<0.5	<0.2
Modulus of elasticity, GPa	200	—	520–690	310–450	310–410	850	820–1050
Density, kg/m^3	8600	8000–8700	10,000–15,000	5500–5800	4000–4500	3500	3500
Volume of hard phase, %	7–15	10–20	70–90	—	100	95	95
Melting or decomposition temperature, °C	1300	—	1400	1400	2000	1300	700
Thermal conductivity, W/m K	30–50	—	42–125	17	29	13	500–2000
Coefficient of thermal expansion, $\times 10^{-6}$/°C	12	—	4–6.5	7.5–9	6–8.5	4.8	1.5–4.8

*The values for polycrystalline diamond are generally lower, except for impact strength, which is higher.

Characteristics of tool material

General Characteristics of Cutting-tool Materials (These Tool Materials Have a Wide Range of Compositions and Properties; Overlapping Characteristics Exist in Many Categories of Tool Materials)

	High-speed steels	Cast-cobalt alloys	Uncoated carbides	Coated carbides	Ceramics	Polycrystalline cubic boron nitride	Diamond
Hot hardness	→						
Toughness	←						
Impact strength	←						
Wear resistance	→						
Chipping resistance	←						
Cutting speed	→						
Thermal-shock resistance	←						
Tool material cost	→						
Depth of cut	Light to heavy	Light to heavy	Light to heavy	Light to heavy	Light to heavy	Light to heavy	Very light for single-crystal diamond
Processing method	Wrought, cast, HIP[*] sintering	Cast and HIP sintering	Cold pressing and sintering	CVD or PVD[†]	Cold pressing and sintering or HIP sintering	High-pressure, high-temperature sintering	High-pressure, high-temperature sintering

Source: After R. Komanduri.
[*] Hot-isostatic pressing.
[†] Chemical-vapor deposition, physical-vapor deposition.

Characteristics of tool material

General Operating Characteristics of Cutting-tool Materials

Tool materials	General characteristics	Modes of tool wear or failure	Limitations
High-speed steels	High toughness, resistance to fracture, wide range of roughing and finishing cuts, good for interrupted cuts	Flank wear, crater wear	Low hot hardness, limited hardenability, and limited wear resistance
Uncoated carbides	High hardness over a wide range of temperatures, toughness, wear resistance, versatile, wide range of applications	Flank wear, crater wear	Cannot use at low speeds because of cold welding of chips and microchipping
Coated carbides	Improved wear resistance over uncoated carbides, better frictional and thermal properties	Flank wear, crater wear	Cannot use at low speeds because of cold welding of chips and microchipping
Ceramics	High hardness at elevated temperatures, high abrasive wear resistance	Depth-of-cut line notching, microchipping, gross fracture	Low strength and low thermomechanical fatigue strength
Polycrystalline cubic boron nitride (cBN)	High hot hardness, toughness, cutting-edge strength	Depth-of-cut line notching, chipping, oxidation, graphitization	Low strength, and low chemical stability at higher temperature
Diamond	High hardness and toughness, abrasive wear resistance	Chipping, oxidation, graphitization	Low strength, and low chemical stability at higher temperatures

Source: After R. Komanduri and other sources.

Common tool materials

- Materials used for dies and molds in casting, forming, and shaping metallic and non-metallic materials are:

1. High-speed steels
2. Cast-cobalt alloys
3. Carbides
4. Coated tools
5. Alumina-based ceramics
6. Cubic boron nitride
7. Silicon-nitride-based ceramics
8. Diamond
9. Whisker-reinforced materials and nanomaterials

Common tool materials

1. **Tool carbon steels** (It contain 0.6 – 1.4 percent carbon and low percentages of Mn, Si, S, P, and heat treated, it withstand temperatures < 250°C)
2. **Alloy tool steels** (The cutting performance of steel can be improved by adding alloying elements such as chromium (Cr), vanadium (V), molybdenum (Mo) and tungsten (Tn). When these steels properly heat treated, they can work at temperatures up to 300°C.)
3. **High speed steels** (It contain 8 – 19% tungsten and 3.8 – 4.6% chromium. They can withstand temperatures up to 600°C)
4. **Cemented carbides**

   Straight tungsten cemented carbide:

   Titanium -Tungsten cemented carbides:

   Titanium – Tantalum – Tungsten cemented carbides:

Ceramic tool materials

Ceramic materials are made by compacting followed by sintering of aluminum oxides (or other ceramics) at high temperature (1700°C). They are able to machine all materials at very high cutting speeds with higher surface finish and no coolant is required.

Diamonds

Diamonds are the hardest materials; they can work up to 1500°C. It is found in nature or synthetically produced from ordinary graphite by subjecting it to extremely high pressures and temperatures.

Cubic Boron Nitride (CBN)

Cubic Boron Nitride is the hardest known material next to diamond.

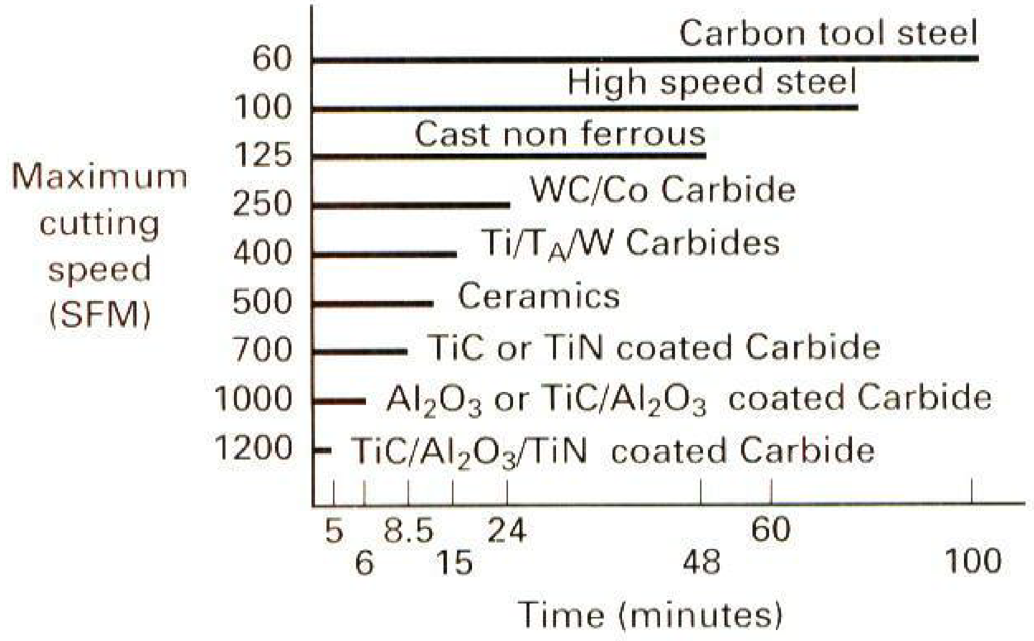
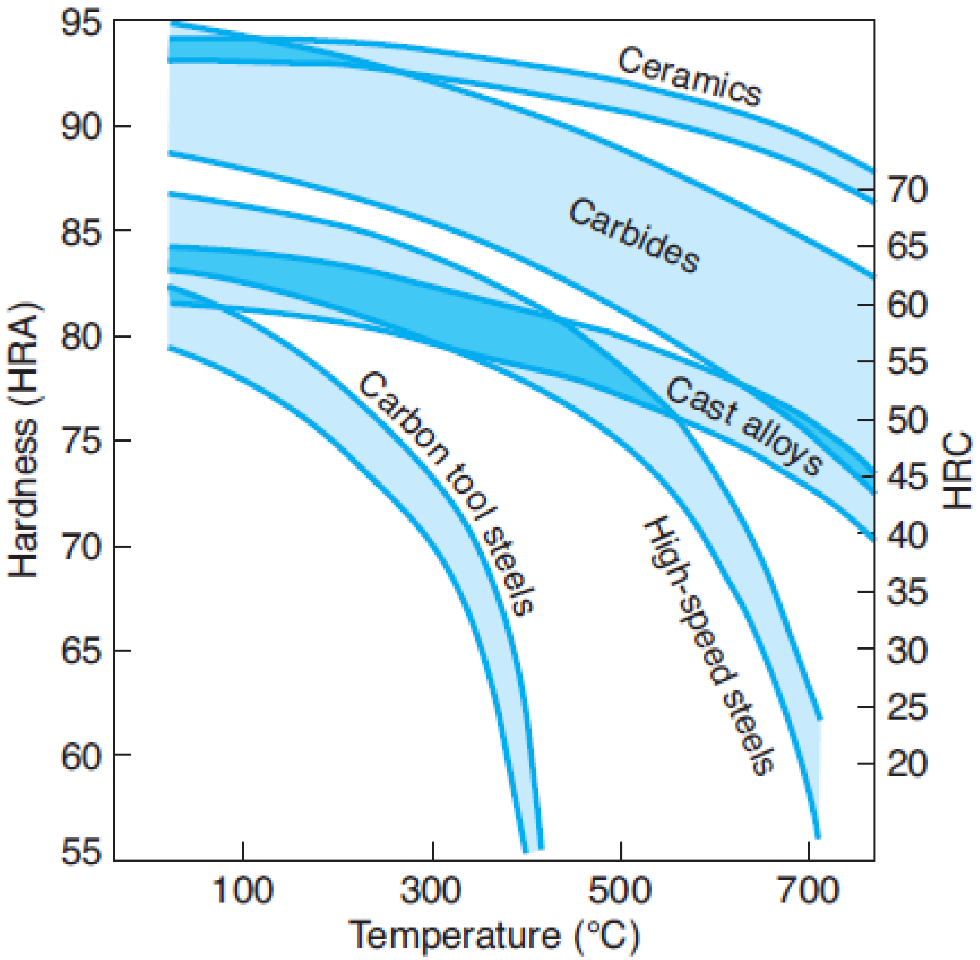


Figure 2.5: Improvement in cutting tool materials have reduced machining time

Comparison of common tool materials hardness at elevated temperatures



Typical hot hardness relationship for selected tool materials. Plain carbon steel shows a rapid loss of hardness as temperature increases, while cemented carbide and ceramics are significantly harder at elevated temperatures.

High-speed Steels

- *High-speed steel* (HSS) tools were developed to machine at higher speeds than was previously possible
- They can be hardened to various depths, have good wear resistance and are inexpensive
- There are two basic types of high-speed steels: **molybdenum** (*M-series*) and **tungsten** (*T-series*)
- High-speed steel tools are available in wrought, cast and powder-metallurgy (sintered) forms
- They can be **coated** for improved performance

Cast-cobalt Alloys

- *Cast-cobalt alloys* have high hardness, good wear resistance and can maintain their hardness at elevated temperatures
- They are not as tough as high-speed steels and are sensitive to impact forces
- Less suitable than high-speed steels for interrupted cutting operations

Carbides

- Also known as *cemented* or *sintered carbides*
- They have the following characteristics:

1. High hardness over a wide range of temperatures
2. High elastic modulus
3. High thermal conductivity
4. Low thermal expansion
5. Versatile
6. Cost-effective tool for a wide range of applications

Carbides: Tungsten Carbide

- *Tungsten carbide* (WC) consists of tungsten-carbide particles bonded together in a cobalt matrix
- As the cobalt content increases, the strength, hardness, and wear resistance of WC decrease
- Its toughness increases because of the higher toughness of cobalt

Carbides: Titanium Carbide

- Consists of a nickel–molybdenum matrix
- Has higher wear resistance than tungsten carbide but is not as tough
- Suitable for machining hard materials and for cutting at speeds higher than tungsten carbide

Carbides:

Classification of Carbides

- ISO standards for carbide grades are classified using the letters P, M, and K

ISO Classification of Carbide Cutting Tools According to Use

Symbol	Workpiece material	Color code	Designation in increasing order of wear resistance and decreasing order of toughness in each category (in increments of 5)
P	Ferrous metals with long chips	Blue	P01, P05–P50
M	Ferrous metals with long or short chips, nonferrous metals	Yellow	M10–M40
K	Ferrous metals with short chips, nonferrous metals, nonmetallic materials	Red	K01, K10–K40

Classification of Tungsten Carbides According to Machining Applications

ISO standard	ANSI classification number (grade)	Materials to be machined	Machining operation	Type of carbide	Characteristics of: Cut	Characteristics of: Carbide
K30–K40	C1	Cast iron, nonferrous metals, and nonmetallic materials requiring abrasion resistance	Roughing	Wear-resistant grades; generally straight WC–Co with varying grain sizes	Increasing cutting speed	Increasing hardness and wear resistance
K20	C2		General purpose		↓ ↑	↓ ↑
K10	C3		Light finishing			
K01	C4		Precision finishing		Increasing feed rate	Increasing strength and binder content
P30–P50	C5	Steels requiring crater and deformation resistance	Roughing	Crater-resistant grades; various WC–Co compositions with TiC and/or TaC alloys	Increasing cutting speed	Increasing hardness and wear resistance
P20	C6		General purpose		↓ ↑	↓ ↑
P10	C7		Light finishing			
P01	C8		Precision finishing		Increasing feed rate	Increasing strength and binder content

Note: The ISO and ANSI comparisons are approximate.

Coated Tools

- New alloys and engineered materials are being developed to have high strength and toughness, abrasive and chemically reactive with tool materials
- Coatings have unique properties:

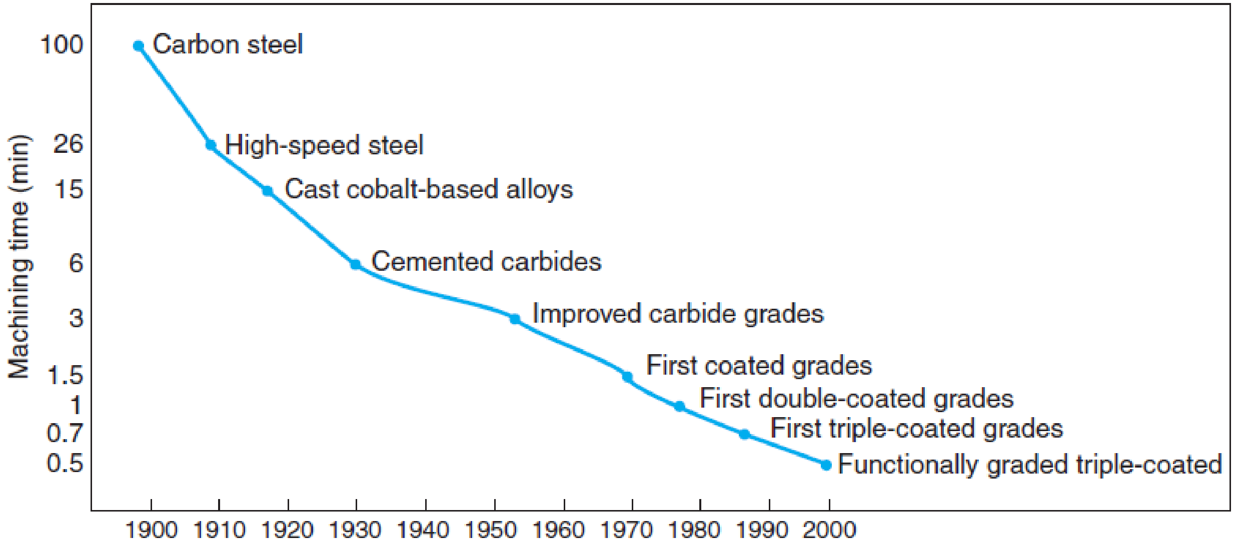
1. Lower friction
2. Higher adhesion
3. Higher resistance to wear and cracking
4. Acting as a diffusion barrier
5. Higher hot hardness and impact resistance

Coated Tools:

Coating Materials and Coating Methods

- Common coating materials are:

1. Titanium nitride
2. Titanium carbide
3. Titanium carbonitride
4. Aluminum oxide



Reduction in machining time as a result of improved cutting tool materials

Coated Tools:

Coating Materials and Coating Methods

- Coatings are applied on cutting tools and inserts by two techniques:

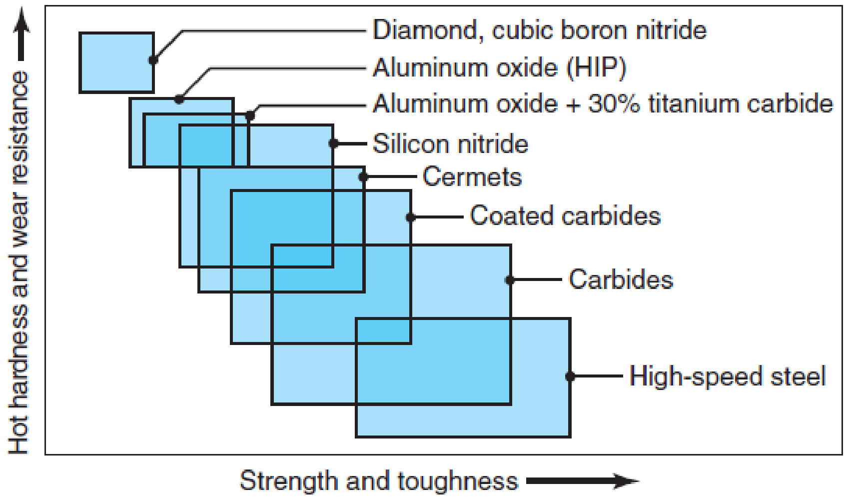
1. **Chemical-vapor deposition** (CVD)
2. **Physical-vapor deposition** (PVD)

- Coatings have the following characteristics:

1. **High hardness**
2. **Chemical stability** and **inertness**
3. **Low thermal conductivity**
4. **Compatibility and good bonding**
5. **Little or no porosity**

Alumina-based Ceramics

- **Ceramic** tool materials consist of fine-grained and high-purity **aluminum oxide**
- Additions of titanium carbide and zirconium oxide improve toughness and thermal shock resistance
- *Alumina-based ceramic* tools have very high abrasion resistance and hot hardness



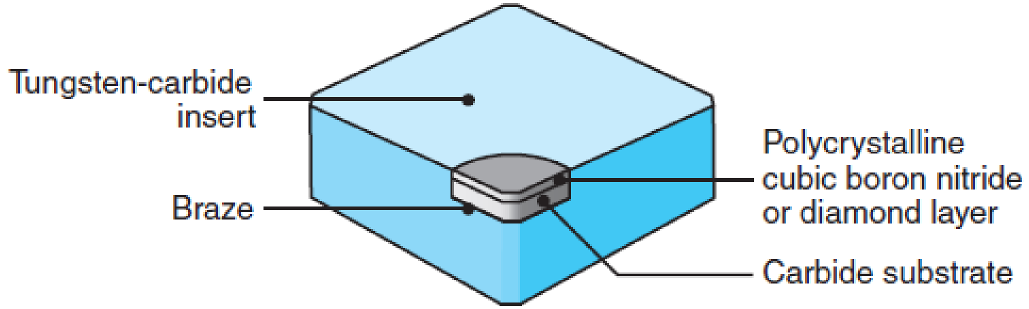
Alumina-based Ceramics

Cermets

- Consist of ceramic particles in a metallic matrix
- They are chemical stability and resistance to built-up edge formation
- But they are brittle, expensive and limited usage

Cubic Boron Nitride

- *Cubic boron nitride (CBN)* is the hardest material available after diamond
- CBN provides shock resistance, high wear resistance and cutting-edge strength
- At elevated temperatures, it is chemically inert to iron and nickel
- Its resistance to oxidation is high and suitable for cutting hardened ferrous and high-temperature alloys

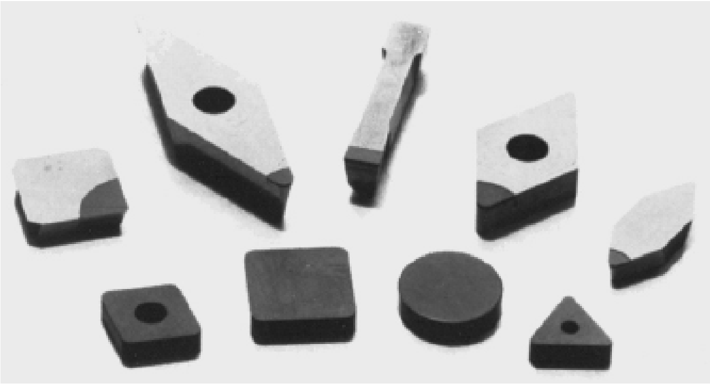


Silicon-nitride-based Ceramics

- *Silicon-nitride* (SiN) *based ceramic* tool materials consist of silicon nitride with various additions of aluminum oxide, yttrium oxide and titanium carbide
- Tools have high toughness, hot hardness and good thermal-shock resistance
- Due to chemical affinity to iron at elevated temperature, SiN-based tools are not suitable for machining steels

Diamond

- The hardest known material is diamond
- They have low friction, high wear resistance and the ability to maintain a sharp cutting edge
- It is used when a good surface finish and dimensional accuracy are required
- *Synthetic* or industrial *diamonds* are used, as natural diamond has flaws and performance can be unpredictable
- As diamond is brittle, tool shape and sharpness are important



Tool Costs and Reconditioning of Tools

- *Tool costs* depend on the tool material, size, shape, chip-breaker features and quality
- The cost of an individual insert is relatively insignificant
- Cutting tools can be **reconditioned** by resharpening them
- Reconditioning of coated tools also is done by recoating them

Methods of fixation of carbides, ceramics & diamond tools

The cutting tools made from carbides, ceramic and diamonds are available in the form of tips (inserts). These inserts can be clamped by using one of the two methods:

Brazing

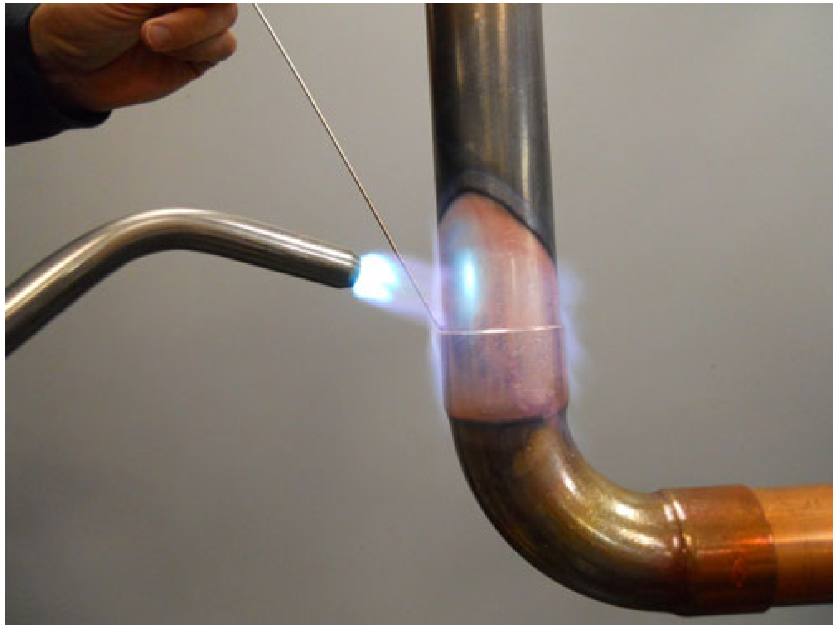
In this method of fixation, the tool bits are bonded with the shank by applying soldering/brazing materials.

Mechanical clamping

Mechanical clamping is used for cemented carbides, ceramics, and other hard materials. In this method the cemented carbide, ceramic, and diamond inserts clamped mechanically with the tool shank.

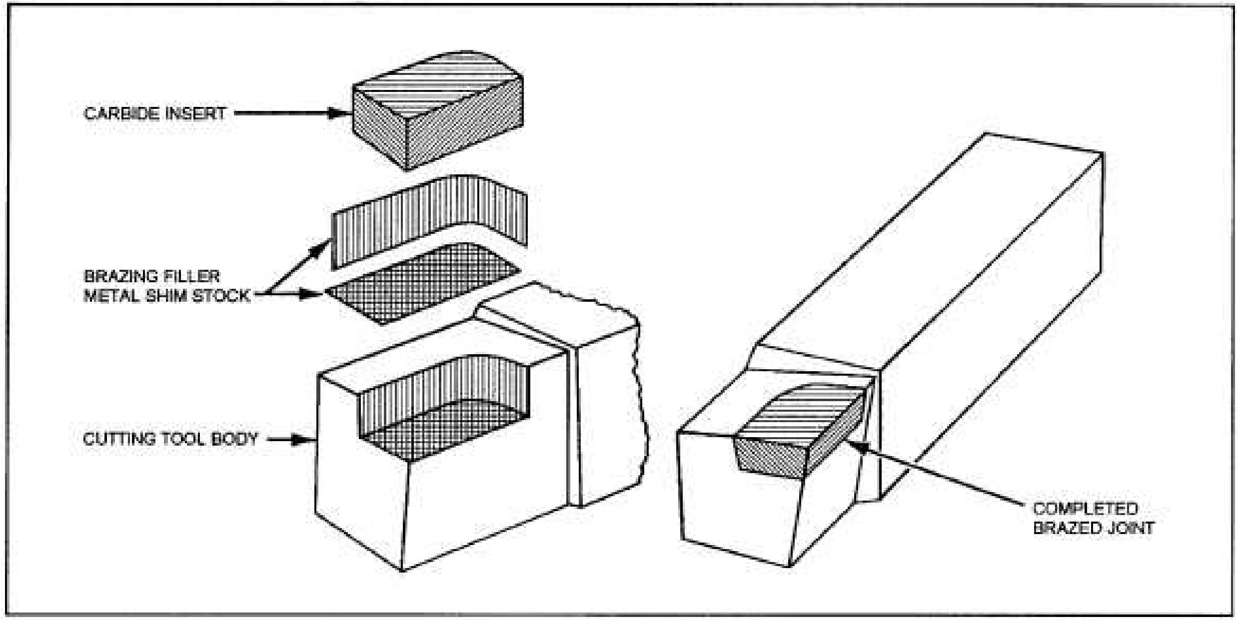
Methods of fixation of sintered carbides, ceramics & diamond tools

Brazing is a metal-joining process in which two or more metal items are joined together by melting and flowing a filler metal into the joint, the filler metal having a lower melting point than the adjoining metal.

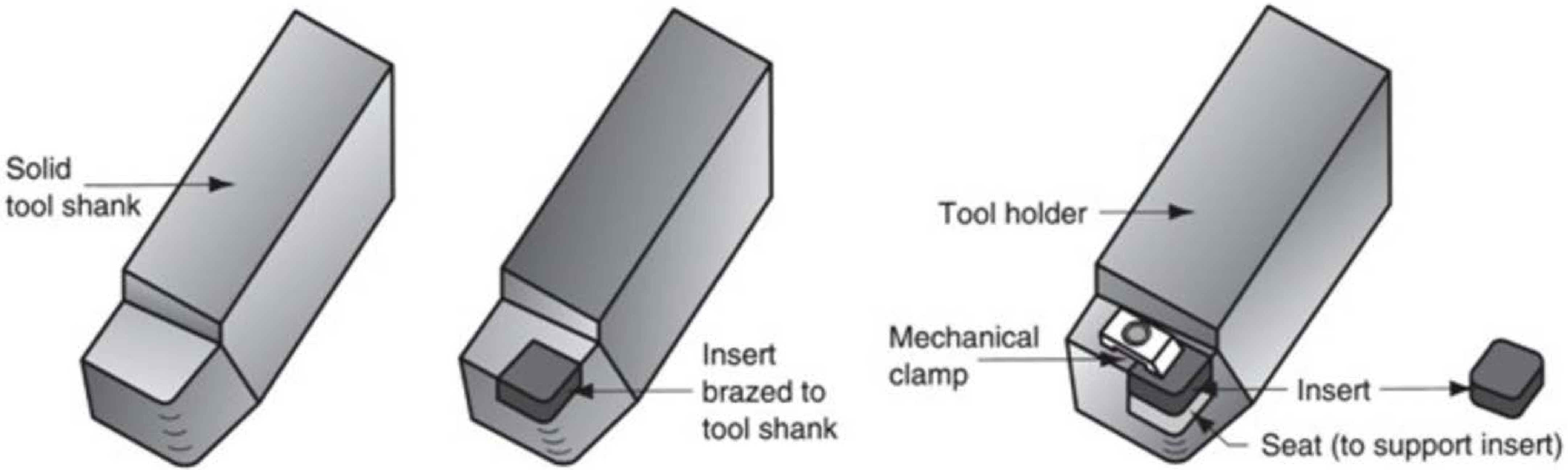


Methods of fixation of sintered carbides, ceramics & diamond tools

Brazing



Methods of fixation of sintered carbides, ceramics & diamond tools

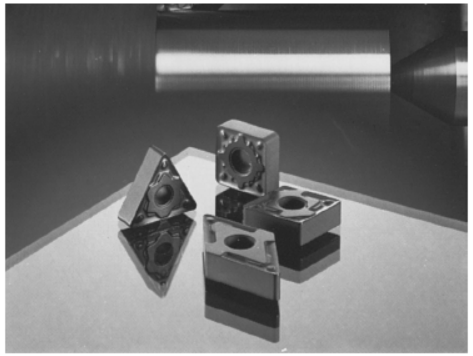


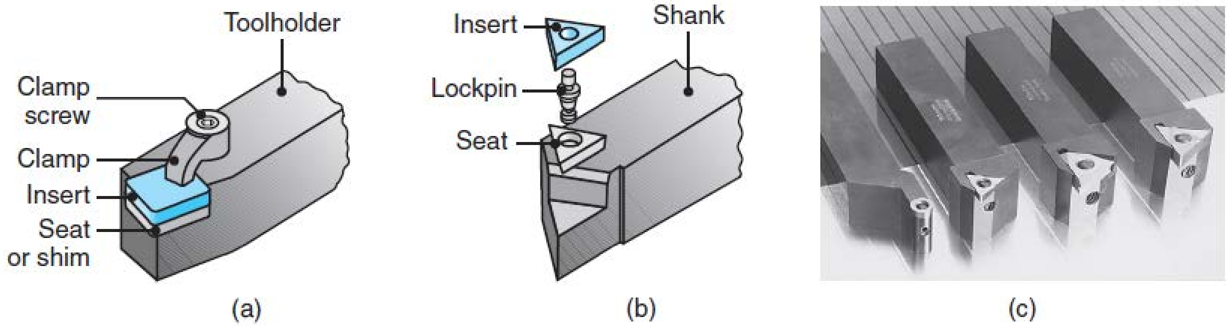
(a) Solid tool (b) Brazed insert (c) Mechanically clamped insert

Methods of fixation of sintered carbides, ceramics & diamond tools

Carbides: Inserts

- High-speed steel tools are shaped for applications such as drill bits and milling and gear cutters
- *Inserts* are individual cutting tools with several cutting points
- Mechanical clamping is the preferred method of securing an insert and insert has **indexed** (rotated in its holder) to make another cutting point available

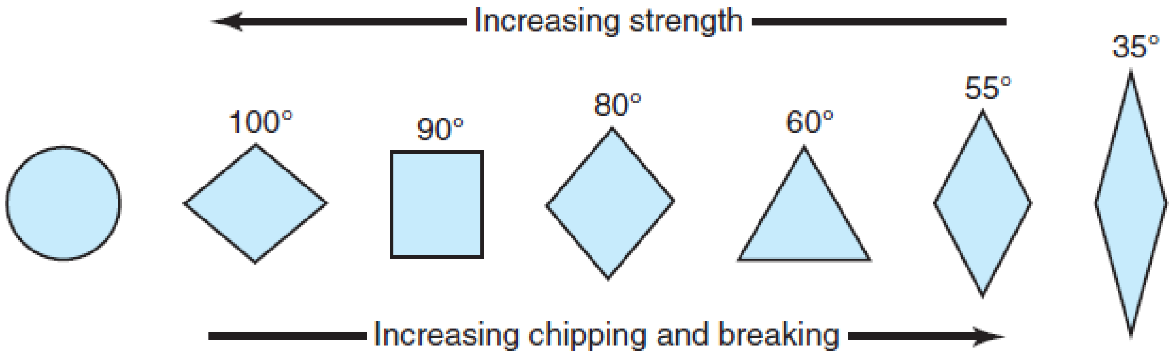




Methods of fixation of sintered carbides, ceramics & diamond tools

Carbides: Inserts

- Available in a variety of shapes: square, triangle, diamond and round
- The smaller the included angle, the lower the strength of the edge



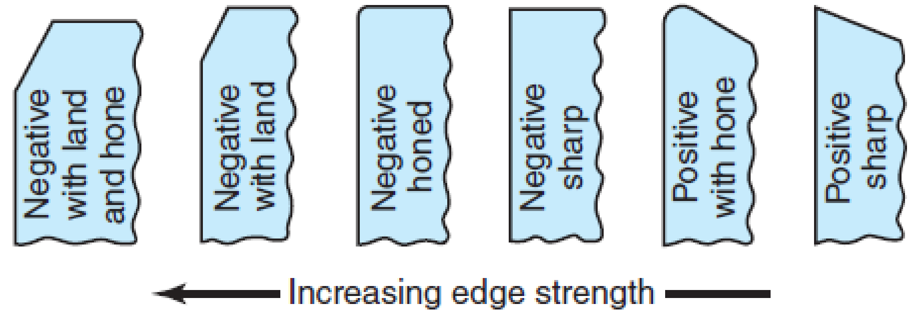
Methods of fixation of sintered carbides, ceramics & diamond tools

Carbides: Inserts

- **Chip-breaker** features on inserts for the purposes of:

1. Controlling chip flow during machining
2. Eliminating long chips
3. Reducing vibration and heat generated

- **Stiffness** of the machine tool is important
- Light feeds, low speeds, and chatter are crucial as they tend to damage the tool's cutting edge



Disadvantages of mechanical clamping

- Mechanical clamping of cutting inserts does not always ensure a contact stiffness that is sufficiently high to prevent vibrations which develop in machining.
- These vibrations shorten the life of the insert and often produce machined surfaces with poor finish.
- The clamping arrangement is often of comparatively large size, which in many cases limits the cutting parameters of the tool such as depth of cut, width of cut.

Disadvantages of brazing

- Micro cracks are often produced due to the high temperature of the brazing operation. The proportion of rejects due to cracks in tips is 10 – 40%.
- High skills is required for brazing.
- Difficulty in changing the worn insert.

Cutting Fluids

- *Cutting fluids* are used to:

1. Reduce friction and wear
2. Cool the cutting zone
3. Reduce forces and energy consumption
4. Flush away the chips from the cutting zone
5. Protect the machined surface from environmental corrosion

- Depending on the type of machining operation, a **coolant**, a **lubricant**, **or** both are used
- Effectiveness of cutting fluids depends on type of machining operation, tool and workpiece materials and cutting speed

Video for cutting fluid:
https://www.youtube.com/watch?v=-o5luQ5Tw80

Cutting Fluids

Cutting-fluid Action

- Cutting fluid seep from the sides of the chip through the *capillary action* of the interlocking network of surface asperities in the tool-workpiece interface
- Discontinuous cutting operations have more straightforward mechanisms for lubricant application, but the tools are more susceptible to thermal shock

Cutting Fluids

Types of Cutting Fluids

- 4 general types:

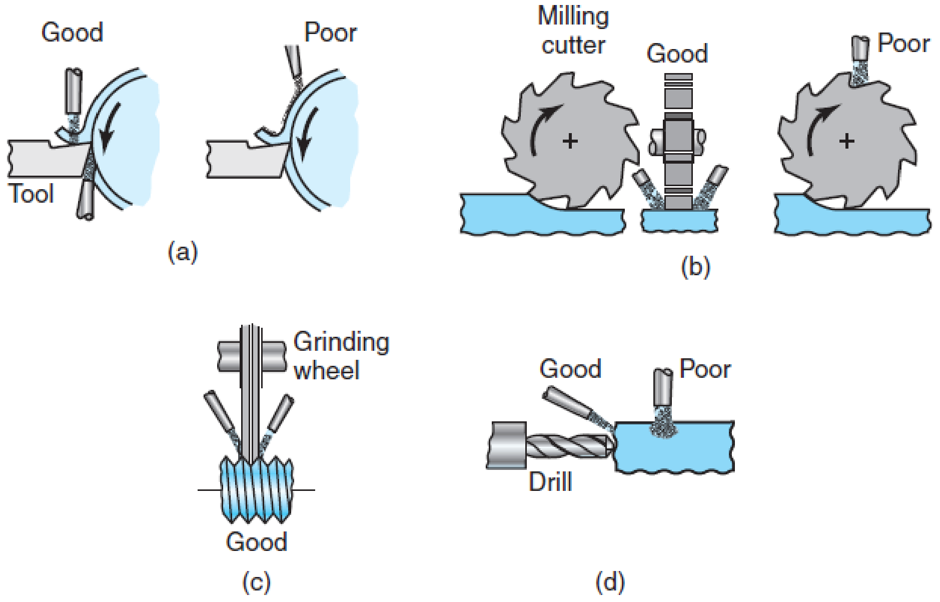
1. **Oils -** mineral, animal, vegetable, compounded, and synthetic oils,
2. **Emulsions -** a mixture of oil and water and additives
3. **Semisynthetics -** chemical emulsions containing little mineral oil
4. **Synthetics -** chemicals with additives

Cutting Fluids

Methods of Cutting-fluid Application

- 4 basic methods:

1. Flooding
2. Mist
3. High-pressure systems
4. Through the cutting tool system



Cryogenic coolant system: https://www.youtube.com/watch?v=de8XlrHRLpY

Through coolant: https://www.youtube.com/watch?v=5R1yRILIcAw

Cutting Fluids

Effects of Cutting Fluids

- Selection of a cutting fluid based on:

1. Workpiece material and machine tools
2. Biological considerations
3. Environment

- Machine-tool operator is in close proximity to cutting fluids, thus health effects is a primary concern
- Progress has been made in ensuring the safe use of cutting fluids
- Recycling involves treatment of the fluids with various additives, agents, biocides, deodorizers and water treatment

Cutting Fluids:

Near-dry and Dry Machining

- Near-dry cutting is the application of a fine mist of an air–fluid mixture containing a very small amount of cutting fluid
- *Dry machining* is effective on steels, steel alloys, and cast irons, but not for aluminum alloys
- One of the functions of a metal-cutting fluid is to flush chips from the cutting zone

Cryogenic Machining

- Using *nitrogen* or *carbon dioxide* as a coolant
- The chips are more brittle and machinability is increased

https://www.youtube.com/watch?v=de8XlrHRLpY